FOUNDATIONS OF MEDICAL IMAGING

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INTRODUCTION

The study of medical imaging is concerned with the interaction of all forms of radiation with tissue and the development of appropriate technology to extract clinically useful information from observations of this interaction. Such information is usually displayed in an image format. Medical images can be as simple as a projection or shadow image—as first produced by Röntgen nearly 100 years ago and utilized today as a simple chest X-ray—or as complicated as a computer reconstructed image—as produced by computerized tomography (CT) using X-rays or by magnetic resonance imaging (MRI) using intense magnetic fields.

Although, strictly speaking, medical imaging began in 1895 with Röntgen's discoveries of X-rays and of the ability of X-rays to visualize bones and other structures within the living body [1], contemporary medical imaging began in the 1970s with the advent of computerized tomography [2, 3]. Early, or what we call *classical*, medical imaging utilizes images that are a direct manifestation of the interaction of some form of radiation with tissue. Three examples will illustrate what we mean by classical imaging. First is the conventional X-ray procedure in which a beam of X-rays is directed through the patient onto a film. The developed film provides a shadow image of the patient which is a direct representation of the passage of X-rays through the body. Although such images are not quantitative, they do provide some measure of the attenuation of X-rays in tissue. Thus a section of soft tissue will appear darker than an equally thick section of bone, which attenuates more of the X-rays. It should be noted that even with current technological developments

conventional X-ray imaging still represents the major imaging procedure at most medical facilities.

As a second example of classical imaging, consider a conventional nuclear medicine procedure. Here a radioactive material is injected into the patient and its course followed by a detector which is moved over the patient in a specified manner. Although the image recorded by the detector generally has poor spatial resolution, its real advantage is that it provides a measure of physiological function from the time course of the radioisotope uptake. Clearly the conventional nuclear medicine image is a direct measure of the location and concentration of the radioactive isotope used.

As a final example of classical imaging, consider conventional medical ultrasound. Here, a pulse of ultrasonic energy is propagated into the patient and the backscattered echo signal is recorded by the same transducer. By angulating or moving the transducer (or by using a transducer array) positionally sequential echo signals are recorded, and a cross-sectional image of the subject is displayed directly on a video monitor. Ultrasound images are really a mapping of echo intensities and are a direct result of the interaction of the ultrasound pulse with tissue.

In this text we will define modern or contemporary medical imaging operationally as a two-part process: (1) the collection of data concerning the interaction of some form of radiation with tissue, and (2) the transformation of these data into an image (or a set of images) using specific mathematical methods and computational tools. Note that our definitions for both classical and modern imaging are consistent with our general definition of medical imaging, given in the first paragraph of this chapter. Note also that modern imaging can be represented as a generalization of classical imaging and that classical imaging is simply a special case of modern imaging in which the image forms directly from the interaction process. Whereas classical imaging is direct and intuitive, modern imaging is indirect and, in many cases, counter intuitive. Since modern images are formed by processing, reformulating, or reconstructing an image from the tissue/radiation interaction data base, the process is often referred to as "reconstruction" and the image as a "reconstructed image."

The first device capable of producing true reconstructed images was developed by G. N. Hounsfield [2] in 1972 at EMI in England. Hounsfield's X-ray computerized tomograph device was based in part on mathematical methods developed by A. M. Cormack [4] a decade earlier. For their efforts Hounsfield and Cormack were awarded the Nobel Prize in medicine in 1979. Put quite simply, CT imaging is based on the mathematical formalism that states that if an object is viewed from a number of different angles, then a cross-sectional image of it can be computed (or "reconstructed"). Thus X-ray CT yields an image that is essentially a mapping of X-ray attenuation or tissue density.

The introduction of X-ray CT in 1972 represents the real beginning of modern imaging and has altered forever our concept of imaging as merely

Table 1-1 3-D image reconstruction algorithms

2-D and 3-D Projection Reconstruction	2-D Projection Reconstruction	Parallel-Beam Mode
		Fan-Beam Mode
	3-D Projection Reconstruction	Parallel-Beam Mode
		Cone-Beam Mode
Iterative Method	Algebraic Reconstruction Technique (ART)	
	Maximum Likelihood Reconstruction (MLR) or Expectation Maximization (EM) Reconstruction	
Fourier Reconstruction	Direct Fourier Reconstruction (DFR)	
	Direct Fourier Imaging (DFI) in NMR	

taking a picture. It has also led to the development of 3-D imaging and is making quantitative imaging a reality. The application of reconstructive tomography to conventional nuclear medicine imaging has led to the development of two new imaging modalities: single photon emission computed tomography (SPECT) and positron emission tomography (PET). Similar applications to the laboratory technique of nuclear magnetic resonance (NMR) has led to magnetic resonance imaging (MRI). The CT concept is currently being extended to 3-D magnetoencephalography, electrical impedance tomography, and photon migration tomography, to name a few. Inherent to the development of these new imaging modalities has been the development of new reconstruction techniques, which are detailed in Table 1-1.

In this chapter we seek to provide a brief historical perspective for the various medical imaging modalities that are currently important. The various techniques are shown in Figs. 1-1 and 1-2 where they are characterized by the interrogation wavelengths. A parallel sequence will be followed in the succeeding chapters which provide more detailed discussions of the various imaging modalities. Although the various imaging techniques will, of necessity, be treated separately, our goal is to provide a unified approach to the field of medical imaging.

1-1 THE BEGINNING WITH X-RAYS

The history of medical imaging really began on November 8, 1895, when Wilhelm Konrad Röntgen reported the discovery of what he called "a new